Refining the Oort Constants: the case for a smaller Milky Way

Rob P. Olling, Michael R. Merrifield

University of Southampton, Department of Physics and Astronomy, Southampton SO17 1BJ, United Kingdom

to appear in the proceedings of the "Workshop on Galactic Halos", Santa Cruz, August 1997 (ASP Conference Series

Abstract.

The local stellar kinematics of the Milky Way, parameterized by the Oort constants A and B, depend on the local gradient of the rotation curve, its absolute value (Θ_0), and the distance to the Galactic center (R_0). The surface density of interstellar gas in the Milky Way varies non-monotonically with radius, and so contributes significantly to the local gradient of the rotation curve, and the Oort constants. Because of this, the Oort *functions* $A(R)$ and $B(R)$ differ significantly from the dominant $\sim \Theta_0/R$ dependence, in the Solar neighborhood and other locations in the Galaxy. These models may explain the ~40% difference between the values for $2AR_0$ derived from radial velocity data originating in the inner and outer Galaxy (Merrifield 1992). Incorporating these local non-linearities explains the significant differences between the Oort constants derived from nearby stars ($d \leq 1$ kpc; Hanson 1987=H87) and distant Cepheids ($d = 0.5 - 6$ kpc; Feast & Whitelock 1997=FW97). However, a consistent picture only emerges if one adopts small values for the Galactic constants: $R_0 = 7.1 \pm 0.4$ kpc, and $\Theta_0 = 184 \pm 8$ km s^{-1}. These values are consistent with most kinematical methods of determining R_0, including the proper motion of Sgr A* (Backer 1996), the direct determination of R_0 using water masers (7.2 ± 0.7 kpc, Reid 1993), and constraints set by the shape of the Milky Way's dark halo (Olling & Merrifield 1997b=OM97b).

1. Introduction

Due to our location within the Milky Way and the modest uncertainties in R_0 (7.7 ± 0.7 kpc; Reid 1993) and Θ_0 (200 ± 20 km s^{-1}; Sackett 1997), the rotation curve of the Milky Way, $\Theta(R)$, is difficult to establish (Fich & Tremaine 1991; Olling & Merrifield 1997a=OM97a). Stellar kinematical data in the form of proper motions and radial velocities can be used to constrain the Galactic constants via the Oort *functions*: $A(R) = \frac{1}{2}\left(\frac{\Theta(R)}{R} - \frac{d\Theta(R)}{dR}\right)$ and $B(R) = -\frac{1}{2}\left(\frac{\Theta(R)}{R} + \frac{d\Theta(R)}{dR}\right)$.

Unfortunately, the available observations of the Milky Way's rotation curve are not good enough to calculate the derivatives of $\Theta(R)$ directly. Instead, we fit mass models to the observations and calculate the derivatives from the model rotation curves. The dominant contributors to the total mass are the stellar disk and the dark matter (DM) halo, which are believed to be fairly smoothly distributed with radius. However, the distribution of interstellar hydrogen (ISM) shows density enhancements such as rings and arms, which will produce a contribution to $\Theta(R)$ that varies non-

monotonically with radius. This effect gives rise to local features superimposed on the dominant Θ/R behavior of the Oort functions (Fig. 1). On larger scales, the Oort functions follow the no-ISM relations (dotted line).

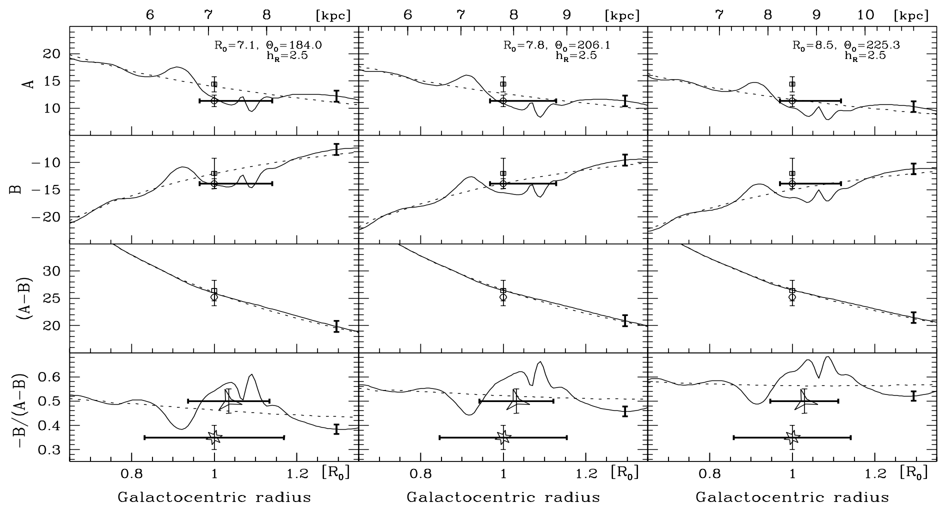

Fig. 1. The Oort functions, $A(R)$ $B(R)$, and $(A-B)$ [km s^{-1}kpc^{-1}] as derived for three model rotation curves. The solid lines are derived from the full mass model, the dashed lines have no gas component. The various observational estimates of these quantities are also shown, with the horizontal error bars indicating the radial range over which the observations effectively averaged. H87's and the IAU standard values (Kerr & Lynden-Bell 1986=KLB86) are plotted (squares and circles), as well as the velocity dispersion ratios of local stars (triangles and hexagons, bottom panel). Notice the ~40% difference between the values of $2AR_0$ inferred from extrapolating the inner and outer Galaxy data, similar to Merrifield's (1992) observational findings.

From Fig. 1 it is clear that if the radial extend of the stellar kinematical surveys is more than a few hundred parsec, it is imperative to take the slope in the Oort functions (a few km s^{-1}kpc^{-2}) into account. However, notice that $A(R)$ and $B(R)$ are almost flat in the first kpc beyond the Solar circle. This is the region sampled by the Lick Northern Proper Motion stars used in Hanson's (1987) determination of the Oort constants. Thus, we compared his values (A=11.3 $\pm$ 1.1, and B=-13.9 $\pm$ 0.9 km s^{-1}kpc^{-1}) with our model predictions. We also use the combinations $(A-B)$ and $-B/(A-B)$ as constraints (for details, see OM97a). Inspection of Figure 1, reveals that models with small values for the Galactic constants fit the observations better than the values currently considered best (middle panels) and the IAU values (rightmost panels).

2. Results

We can formalize the constraints placed on the values of the Galactic constants by calculating a χ^2 statistic comparing the five observed combinations of the Oort constants in Fig. 1 to the values predicted by the models. Because of the radial dependence of the Oort functions, we compared the model and observed values over the radial extend of the observations (horizontal error bars). Since these regions are approximately equal to the size of the epicycles of the stellar populations studied, we expect that the Oort functions can show structure on these scales. The χ^2 statistics were

calculated for a range of values for R_0 and Θ_0. The best-fit (minimum-χ^2) values are: $R_0 = 7.1 \pm 0.4$ kpc, and $\Theta_0 = 184 \pm 8$ km s^{-1}. In Figure 2, we plot the probability that any given values for R_0 and Θ_0 are consistent with the observed Oort constraints. For example, the official IAU-sanctioned values of $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1}are ruled out at the 99% confidence level. Comparing our best fit values with R_0 determinations based on kinematical constraints (see Reid 1993 for a compilation), we find that all are consistent with the leaner Galaxy we propose here. In particular, R_0=7.1 kpc is entirely consistent with its only *direct* determination employing H_2O masers proper motions (R_0= 7.2 $\pm$ 0.7 kpc, Reid 1993). Furthermore, these Galactic constants are consistent with the proper motion of Sgr A* (Backer 1996). From a new and completely independent analysis based on the shape of the Galaxy's dark matter halo, we find similar constraints on the Galactic constants (OM97b).

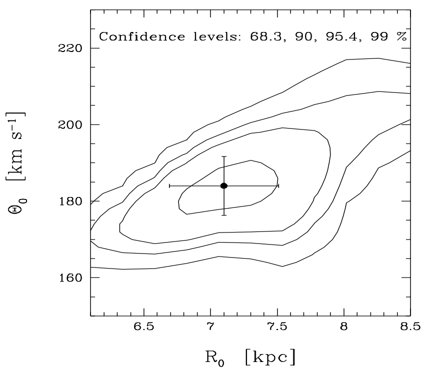

Fig. 2. The contours of equal likelihood as a function of R_0 and Θ_0, calculated by comparing the model values with the observed A, B, $A-B$, and $-B/(A-B)$ constraints presented in Fig. 1. The best-fit minimum-χ^2 values for R_0 , Θ_0, and their 1-σ errors are also indicated. The IAU standard values are R_0=8.5 kpc, and Θ_0=220 km s^{-1}.

The Oort constants derived from nearby stars ($d \leq 1$ kpc, H87) differ significantly ($\sim 3\sigma$) from the values derived at large distances ($d = 0.5 - 6$ kpc, FW97). However, extrapolating our best fit model from the distant Galaxy towards the Solar position, i.e., following the no-ISM line in Fig. 1, yields A and B's very close to those of FW97. Furthermore, our models and the FW97 models predict almost identical Cepheid proper motions. We conclude that the discrepancy between the H87 and FW97 Oort constants is caused by the non-linear behavior in the Solar neighborhood and that a consistent picture only emerges for a leaner Milky Way with R_0 =7.1 $\pm$ 0.4 kpc, Θ_0=184 $\pm$ 8 km s^{-1}.

References

Backer D.C., 1996, in Blitz L., Teuben P., eds, Unsolved Problems of the Milky Way
Feast M., Whitelock P., 1997, MNRAS, in press, astro-ph/9706293 (FM97)
Fich M., Tremaine S., 1991, ARA&A, 29, 409
Hanson R.B., 1987, AJ, 94, 409 (H87)
Kerr F.J., Lynden-Bell D., 1986, MNRAS, 221, 1023 (KLB86)
Merrifield M.R., 1992, AJ, 103, 1552
Olling R.P., Merrifield M.R., 1997b, in preparation. Summary in this volume and at astro-ph/9710224 (OM97b)
Olling R.P., Merrifield M.R., 1997b, submitted to MNRAS (OM97a)
Reid M.J., 1993, ARA&A, 31, 345
Sackett P.D., 1997, ApJ, 483, 103